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Generalized Procedure For Assessing Post-Mining Groundwater Supply Potential In The Plains Of Alberta

Heritage Fund

Alberta
LAND CONSERVATION AND
RECLAMATION COUNCIL
Reclamation Research
Technical Advisory Committee

Report #
RRTAC 86-3

GENERALIZED PROCEDURE FOR ASSESSING POST-MINING GROUNDWATER SUPPLY POTENTIAL IN THE PLAINS OF ALBERTA

by

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To assist in technical matters related to the development and administration of the research program the Council appointed the Reclamation Research Technical Advisory Committee (RRTAC). The Committee first met in March, 1978 and consists of eight members representing the Alberta Departments of Agriculture, Energy and Natural Resources, Environment and the Alberta Research Council. The Committee meets regularly to update research priorities, review solicited and unsolicited research proposals, arrange workshops and otherwise act as a referral and coordinating body for Reclamation Research.

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PREFACE

This is one of a series of reports that presents the findings of the Plains Hydrology and Reclamation Project (PHRP), an interdisciplinary study that focuses primarily on hydrologic aspects of reclamation of surface coal mines in the plains of Alberta. This research has been conducted by the Alberta Research Council, as part of the Alberta Government's Reclamation Research Program. The program is managed by the Alberta Land Conservation and Reclamation Council and is supported by the Heritage Savings Trust Fund.

The focus of the PHRP is to develop a predictive framework that will permit projection of success for reclamation and impact of mining on water resources on a long-term basis. The predictive framework is based on an understanding of processes acting within the landscape so that, in the future, mine sites that are not totally analogous to those that have been studied can be evaluated as well.

The project involves a holistic approach to reclamation by integration of studies of geology, hydrogeology, and soils, not only in the proposed mining area, but also in the adjoining unmined areas. This approach permits the assessment of impacts and of long-term performance, not only in reclaimed areas, but also in the surrounding area.

The research of the PHRP has been directed toward the following two major objectives and eight subobjectives.

Objective A

To evaluate the potential for reclamation of lands to be surface mined. The focus is on features of the landscape that make it productive in a broad sense not restricted to revegetation. This objective was organized into five subobjectives.

1. To assess and evaluate the potential for long-term degradation of reclaimed soils through salt buildup.
2. To assess and evaluate the effectiveness of topographic modification and selective placement of materials to

mitigate deleterious impacts on chemical quality of groundwater.

3. To assess the availability of water supply in or beneath cast overburden to support post-mining land use, including both quantity and quality considerations.
4. To evaluate the productivity potential (capability) of post-mining landscapes and the significance of changes in capability as a result of mining.
5. To assess and evaluate limitations to post-mining land use posed by physical instability of cast overburden.

Objective B

To evaluate the long-term impact of mining and reclamation on water quantity and quality. This objective was organized into three subobjectives.

1. To assess and evaluate the long-term alteration of quality of groundwater in cast overburden and surface water fed from mine spoil as a result of the generation of weathering products.
2. To assess and evaluate infiltration, groundwater recharge, and groundwater-surface water interactions within cast overburden.
3. To characterize the groundwater chemistry generated within cast overburden.

Studies directed at these objectives began in 1979 at the Battle River site in east-central Alberta. Work began in 1982 at a second study area at Highvale Mine south of Lake Wabamun. Significant progress had been made on all project objectives by the end of the first phase of study in March 1984. This present series of reports summarizes the state of our knowledge at the end of this first phase of study. Work is now continuing on the Phase II objectives to gain an even greater understanding of the complex physical and chemical processes in reclaimed landscapes.

The following report is one of three that are directed at Subobjective A-3: To assess the availability of water supply in or beneath cast overburden to support post-mining land use. The other two reports are concerned with the site-specific aspects of locating a post-mining groundwater supply at the two project study sites, Battle River and Highvale. The present report is a compilation of techniques and strategies that evolved from the PHRP evaluation of groundwater supply potential at these two sites. The report is intended to serve as a guide to those individuals involved in such investigations in the future and provides descriptions, with examples, of the general steps involved in assessing the post-mining groundwater supply potential of a site. This report, which is applicable to mine sites from Lake Wabamun on the northwest to Shearness on the southeast, presents generalized conclusions regarding the availability of and exploration for post-mining groundwater supplies at any potential mining site in east-central Alberta.

ABSTRACT

In the plains region of Alberta, the surface mining of coal generally occurs in rural, agricultural areas in which domestic water supply requirements are met almost entirely by groundwater. Consequently, an important aspect of the capability of reclaimed lands to satisfy the needs of a residential component is the post-mining availability of groundwater. This report proposes a sequence of steps or procedures to identify and characterize potential post-mining aquifer. The procedures identified are: (1) Development of an exploration strategy based on five types of potential post-mining aquifers, i) sheet-like sand beds beneath the base of mining, ii) persistent coal beds beneath the base of mining, (iii) discontinuous sand bodies beneath the base of mining, (iv) valley fill and outwash aquifers, and (v) mine spoil aquifers; (2) Evaluation of existing available geologic and groundwater data; (3) Test drilling and instrumentation; (4) Hydraulic testing and water sampling; and (5) Synthesis and interpretation of data from the first four procedures, to characterize both the premining groundwater conditions and the potential post-mining groundwater supply. Water quantity characteristics (yield) are compared to a proposed standard of 0.05 to 0.07 L/s. Water quality characteristics of potential post-mining aquifers are compared to established maximum permissible concentrations in the case of constituents known to have serious adverse effects on human health or compared to the water quality in the existing domestic wells, for constituents that are not harmful to humans. The final product is a compilation of settings in both horizontal and vertical dimensions in which the specified criteria of water quality and quantity are met by the post-mining aquifers.

ACKNOWLEDGEMENTS

This project was supported by the Alberta Heritage Trust Fund and administered by the Reclamation Research Technical Advisory Committee of the Alberta Land Conservation and Reclamation Council.

1. INTRODUCTION

In the Alberta Plains, the surface mining of coal generally occurs in rural, agricultural areas that depend almost entirely on groundwater to meet domestic water supply needs. In addition, in many places, the coal seams are important local aquifers (Moran et al. 1983; Trudell and Li 1981). If reclaimed land in such areas is to be productive and viable in an overall sense, a source of post-mining water supply must be identified for domestic use as well as for watering livestock. Groundwater is the logical choice for post-mining water supply, since it is well suited for application in areas of low population density. The water supply requirements of agricultural land in the plains region of Alberta are most commonly met by groundwater supplied by single, relatively low yield wells without surface storage or treatment. In some areas, geological conditions are such that no aquifer capable of producing adequate amounts of water is available or the quality of the water that can be produced is submarginal for human or livestock consumption. In these areas, dugouts are commonly used for stock watering and needs for human consumption are met by some alternate source such as trucking water, the use of bottled water, or treatment of low quality water. In nearly all areas of potential surface mining of coal, water of adequate quantity and quality is available to meet rural water supply needs either from the coal beds themselves or from permeable units in the overburden. All of the studies that have been conducted indicate that mining will decrease the capability of the landscape to provide adequate rural water supply. As a result of removal of the coal and disruption of the overburden, the permeability structure of the aquifers is disturbed and almost everywhere the ability of the replaced spoil material to yield water to wells is decreased relative to what it was prior to mining. In addition to that, studies show that the chemical quality of the groundwater is significantly degraded. The significance of these changes in the shallow aquifers in mined areas can be major or minor, depending on the geologic setting of a given mine area. In some areas, widespread aquifers that contain potable groundwater are present beneath the base of disturbance and a post-mining water supply can be readily developed at limited cost. In other areas, no such aquifers are present and the post-mining site will resemble neighbouring areas where some alternative means of providing a water supply will have to be found. In still other areas, suitable aquifers are present beneath parts of the project area but not beneath others. These differences have clearly different implications for the post-mining development of the project area.

This report, and its companion reports on the post-mining groundwater supply potential of the Battle River and Highvale study areas (Figure 1), are predicated on the presumption that the provision of an adequate water supply to support the intended post-mining land use should be addressed at the project planning stage of developing a mining area. Including post-mining water supply considerations in the front-end planning of the entire project affords several advantages. The most cost-effective solution to any potential limitations in availability of suitable post-mining water supply can be identified. Any constraints that arise from the water supply picture can be incorporated in a proactive way into the planning process to determine the end land use for the reclaimed area. For example, this land use planning exercise could include options such as the siting of dwellings in appropriate areas in those mine areas where potable groundwater is to be found only in restricted locations. In another vein, the best solution for a site with very limited potential for adequate groundwater supplies might be to configure the land surface to create surface impoundments to support livestock operations.

The identification and characterization of potential post-mining aquifers will be largely site-specific, however, a number of steps or procedures are involved in the process and can be applied to any site. The objective of this report, then, is to identify and describe these steps or procedures in a sequence typical of an investigation, and provide a rationale and expected result for each

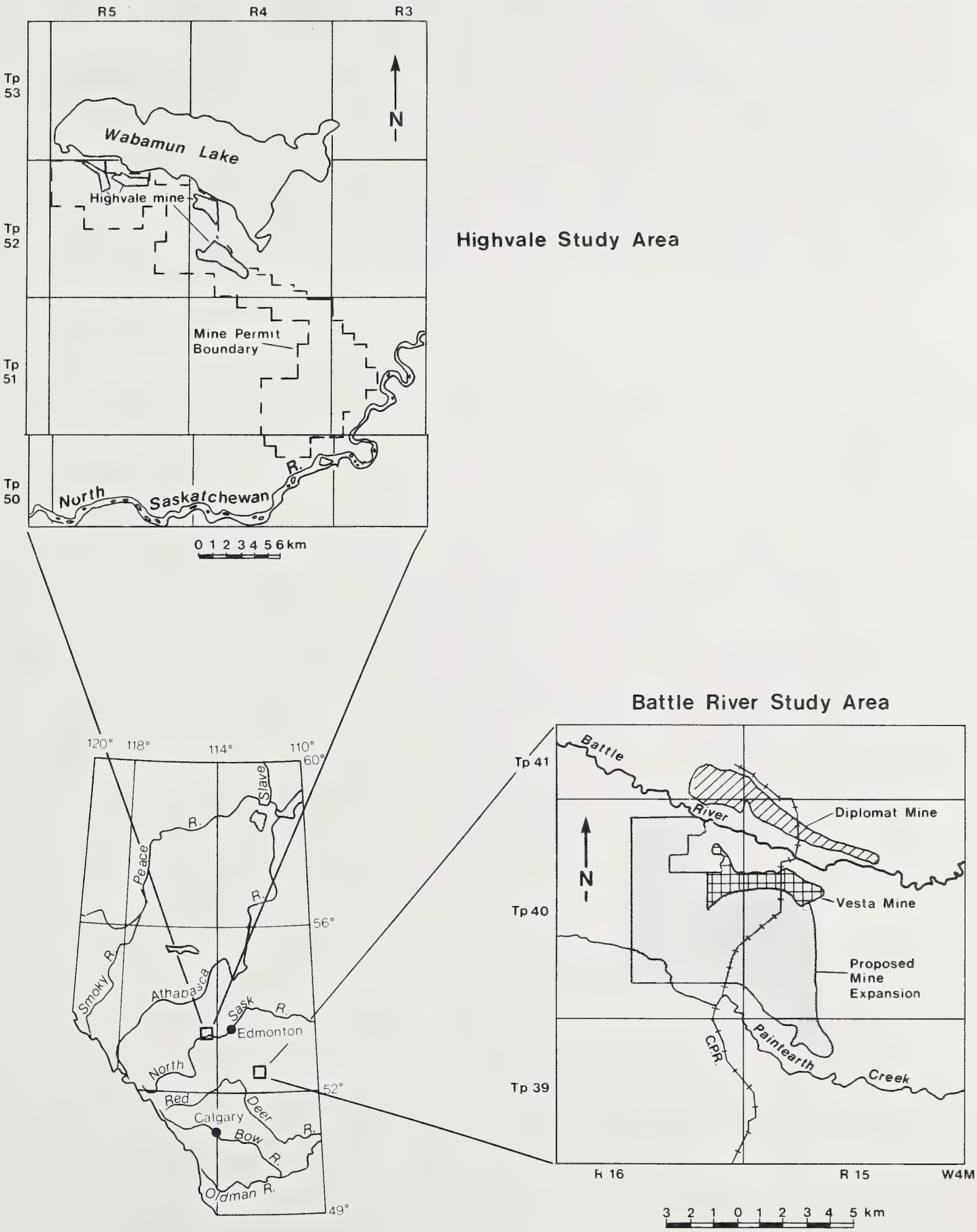

Figure 1. Location of Battle River and Highvale study areas of the Plains Hydrology and Reclamation Project.

procedure. Although this report is only specifically dealing with the procedures for assessing post-mining groundwater supply potential, it is recognized that sources other than groundwater may be viable in specific situations. The report describes the procedures for evaluating post-mining groundwater supply potential in the Alberta Plains, as identified by the Plains Hydrology and Reclamation Project of the Alberta Research Council.

2. REGIONAL GEOLOGICAL SETTING

Nearly all the important present and potential mining areas in the plains of Alberta occur in the lower part of the Horseshoe Canyon Formation or in the Ardley Coal Zone in the Scollard Member of the Paskapoo Formation. In general, the same geological conditions prevail beneath these two coal zones in the region of their subcrop from east of Calgary to the latitude of Edmonton (Figure 2). This report generalizes the geological conditions and is applicable to studies throughout this region.

2.1 JUDITH RIVER (BELLY RIVER) FORMATION

The lowest unit of interest in the region is the Judith River Formation of Cretaceous age, which crops out to the northeast and underlies the entire area (Figure 2). The Judith River Formation consists of gray to greenish gray, thick bedded sandstone, gray clayey siltstone, and gray and green mudstone (Green 1972). The formation, which varies in thickness from 215 m in the south (Kunkle 1962) to 300 m in the north (Alberta Environment 1978), contains two intervals that are sufficiently permeable to constitute aquifers in some areas of the province. At the base of the formation a basal sandstone member is encountered at approximately 300 m beneath the surface in the Camrose-Ryley area (Alberta Environment 1978). A second permeable unit, the Birch Lake Member, lies about 125 m above the basal sandstone member in the northern part of the area (Alberta Environment 1978) and 70 m to 90 m above it in the south (Kunkle 1962).

On the basis of investigations throughout the region, it is unlikely that the sandstones of the Judith River Formation are suitable as post-mining water supply. The sandstone units are at minimum depths of several hundred metres beneath the basal coals of the Horseshoe Canyon Formation and thus would require expensive deep wells. The water is generally too saline for consumption by humans without treatment (Alberta Environment 1978, pp. 14; Alberta Environment 1977a, pp. 24). In addition, considerable gas is

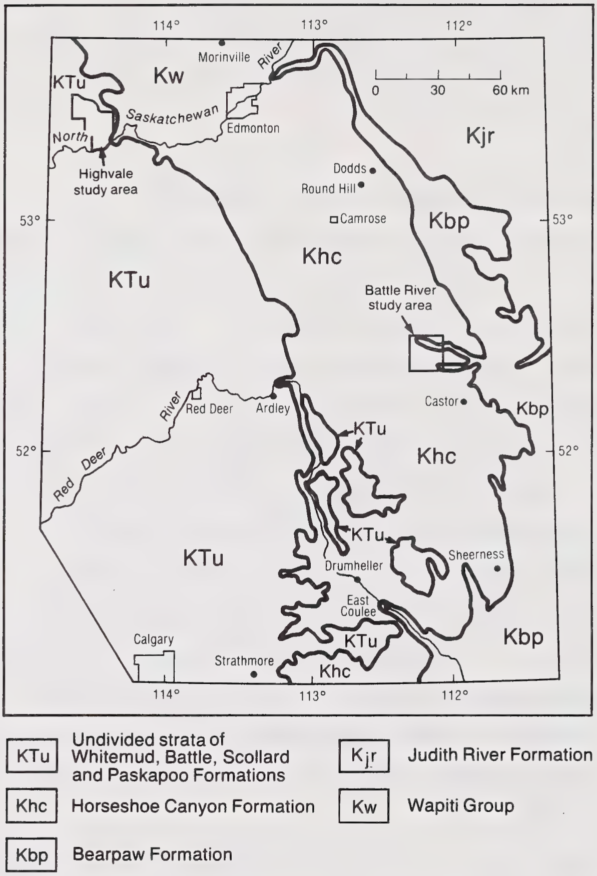

Figure 2. Map showing generalized bedrock geology in the area of east-central Alberta covered by this report.

encountered in many deep wells and gas locking of pumps is a significant problem (Alberta Environment 1978, pp. 14; Alberta Environment 1977a, pp. 21-23).

2.2 BEARPAW FORMATION

The Bearpaw Formation (Figure 2) consists mainly of dark gray marine shale and fine- to medium-grained sandstone that is commonly glauconitic (Given and Wall 1971). The shale weathers to a diagnostic grayish brown colour. Bands of clay ironstone concretions are present in places. The common bentonite beds are useful as local marker beds. The formation, which thins toward the north and west, is reported to be 220 m thick at Shearness (Alberta Environment 1977b, pp. 10), 143 m thick at Castor (Given and Wall 1971), and as much as 600 to 750 m thick in the Camrose-Ryley and Edmonton areas (Alberta Environment 1978, pp. 11). The formation pinches out toward the west and has not been recognized beyond about 100 km west of Edmonton (Williams and Burk 1964). Beneath the erosional edge of the Horseshoe Canyon Formation, three regionally traceable sandstone beds occur in the Bearpaw Formation.

In many places the three sandstone beds in the Bearpaw Formation are sufficiently permeable to produce water to wells. In most places, however, the water quality is not adequate for human consumption without treatment. In certain settings, where the sandstones are recharged directly from the surface or through sand and gravel of Quaternary age, the water quality is good enough to meet individual water supply needs. This type of setting occurs at the Battle River site (Trudell et al. 1985), and may occur elsewhere along the Lower Horseshoe Canyon Coal Zone.

2.3 HORSESHOE CANYON FORMATION

The Horseshoe Canyon Formation (Figure 2) consists dominantly of interbedded gray and brown montmorillonitic siltstone and shale with minor white and light gray feldspathic, clayey sandstone (Maslowski Schutze et al. 1985). The sandstone beds are lenticular and lack lateral continuity. In addition the sandstone is generally so clayey that hydraulic conductivity is low. The entire formation is characterized by the presence of regionally extensive coal seams, which are especially abundant in the lower 150 m of the formation, the Lower Horseshoe Canyon Coal Zone.

Throughout the area underlain by the Horseshoe Canyon Formation, small amounts of groundwater are produced from shallow wells in fractured sandstone and coal. Because of the lenticular nature of the sandstone beds their presence cannot be predicted at any given location. Alberta Environment (1978, pp. 11) reported that the only two zones that contained predictable and adequate water supply potential are the lower coal zone and a sandstone zone about 45 to 135 m below the top of the formation in an area south and west of Edmonton. It is not known whether this sandstone zone extends as far west as the Lake Wabamun area, but if it does it may offer a potential for groundwater supply beneath the Ardley Coal Zone. The Lower Horseshoe Canyon Coal Zone offers little potential as a post-mining water supply. In most of the proposed mining areas in the Lower Horseshoe Canyon Coal Zone, the coals that would constitute the aquifer will be removed by mining. Beneath the Ardley Coal Zone, the Lower Horseshoe Canyon Coal Zone is so deeply buried that hydraulic conductivity is expected to be very low and water quality is likely unacceptable for human consumption without treatment.

2.4 WHITEMUD AND BATTLE FORMATIONS

The Whitemud Formation consists of as much as 20 m of greenish gray, medium to coarse grained, friable sandstone and sand containing uncommon thin, hard, cemented beds (Alberta Environment 1978, pp. 11). The Battle Formation consists of about 8 to 15 m of greenish gray shale containing interbedded siltstone and sandstone. In addition, the formation is characterized by brownish black, waxy, smectitic shale and tuff, tuffaceous shale and bentonite (Alberta Environment 1978, pp. 11). These two units together form a very conspicuous marker horizon. Indications are that there is no potential for development of post-mining groundwater supplies in either of these units.

2.5 PASKAPOO FORMATION

The Ardley Coal Zone occurs at the top of the basal unit in the Paskapoo Formation, the Scollard Member, and as a result this unit is the only interval of interest from the standpoint of assessing the post-mining groundwater supply potential of east-central Alberta. In addition to the thick coal beds at the top of the unit, the Scollard Member consists of as much as 55 m of smectitic siltstone, shale, and sandstone. The sandstone beds are very similar to those in the Horseshoe Canyon Formation in that they are lenticular, lack lateral continuity, and have low hydraulic conductivity because of the abundant interstitial clay. Like the sandstone beds in the lower unit, they are unpredictable in occurrence and cannot be relied on to provide a post-mining groundwater supply. Although in some places adequate permeability is encountered to supply farm wells, such zones are not predictable in location or extent.

3. PROCEDURES FOR EVALUATING POST-MINING WATER SUPPLY

There are two general approaches that may be pursued in the investigation of post-mining groundwater supply potential; we refer to them as the generic and specific approaches. In the generic, or proactive approach, an attempt is made to characterize the water supply conditions for the site as a whole, whereas the specific or reactive, approach considers alternate sources for each existing domestic well that is likely to be impacted by mining. From an operational point of view, the specific approach is often considered to be more attractive since it tends to address immediate problems. In general, however, the generic approach is the more flexible technique, with better long-term applicability to the whole post-mining land use issue. The generic philosophy is especially well suited to areas where hydrostratigraphic units display a reasonable degree of lateral continuity and is less useful at sites where the lateral geologic relationships are more complex.

For either approach, the evaluation of post-mining water supply potential at a site has five principal components: (1) Development of an exploration strategy suited to the geologic setting of the area; (2) Evaluation of existing groundwater and geologic data; (3) Test drilling and instrumentation; (4) Hydraulic testing and water sampling; and (5) Data synthesis and interpretation.

3.1 EXPLORATION STRATEGY FOR EVALUATING POST-MINING WATER SUPPLY

The potential for developing a suitable water supply following mining and reclamation is directly dependent on the geology of the area to be mined. In the plains of Alberta, the options are relatively limited by the characteristics of the coal-bearing sequences. These options can be summarized in order of preference as follows:

1. Laterally persistent, sheet-like sand deposits beneath the base of mining.

2. Widespread coal beds beneath the base of mining.
3. Discontinuous sand bodies beneath the base of mining.
4. Valley fill and outwash deposits of Quaternary age adjacent to the area to be mined.
5. Aquifers within the mine spoil itself.

3.1.1 Sheet-Like Sand Beds

Laterally persistent, sheet-like sand bodies occur in the Bearpaw Formation beneath the lowermost coal zone in the Horseshoe Canyon Formation, such as at the Battle River site (Figure 2; Maslowski Schutze et al. 1985). These sandstone bodies generally have sufficient thickness and hydraulic conductivity to produce an adequate water supply for individual farmsteads. Where the water quality is acceptable, they offer the best option to replace water supplies lost as a result of mining.

The geologic and hydrologic setting of these sand bodies, however, generally results in water containing too much salt to be acceptable for human, and in some places animal, consumption. The higher hydraulic conductivity and greater lateral continuity of these sand bodies compared to sands in the Horseshoe Canyon Formation are a consequence of deposition in a marine margin rather than a fluvial setting. The sediment lying both above and below these sand beds is marine shale, which contains high concentrations of sodium chloride in its interstitial pore fluid. These sand beds lie at least 50 m below the coal that marks the base of mining. As a consequence, they are expected to lie beneath the level of local hydrologic drains at most sites. Therefore, the water in these sand beds is in a sluggish flow system in which flow paths and residence times are long, velocities are low, and diffusion is an important chemical process. The resulting water chemistry is brackish and dominated by sodium chloride. Wells in these and related sandstone beds are reported in places to produce methane.

At sites where the sand beds are recharged through deeply incised glacial meltwater valleys, such as in the eastern part of the

Battle River site, the water quality in these aquifers can be acceptable for human consumption.

The geological environment that was responsible for formation of these sand aquifers was widespread. Such aquifers are expected to be present province-wide beneath the lowermost coal beds in the Horseshoe Canyon Formation. No similar units are known higher in the section. Certainly no analogous aquifers were found beneath the Ardley Coal Zone at the Highvale site (Figure 2). Where these sand aquifers are present, water quality, which is controlled by local recharge, is usually the determining factor in their potential value.

3.1.2 Persistent Coal Beds

If a persistent coal beds were present beneath the maximum depth of mining within a site, it would offer the second most desirable option for development of a post-mining water supply. No such coal unit was found beneath either the Battle River or Highvale sites; however, it is likely that such a situation may occur elsewhere in the province. Where such a coal bed is found, well yield will be a concern. It has been shown that the hydraulic conductivity of coal decreases with depth, presumably as a result of a decrease in number and size of fractures (Moran et al. 1978). In addition, the potential that water quality will be inadequate becomes greater with increased depth.

3.1.3 Discontinuous Sand Bodies

Discontinuous sand bodies that range in width from a few hundred metres to several kilometres and in thickness from a few metres to tens of metres are widespread in coal-bearing sequences throughout the plains of Alberta. In places, wells can be developed in these sand bodies, but in general, the hydraulic conductivity is too low as a result of the abundant interstitial clay or cementation (Maslowski Schutze et al. 1985).

Exploration for all except the largest of these sand bodies beneath the base of mining cannot be treated generically, because their specific locations cannot be predicted by existing sedimentological models. Thus, this type of sand body may meet individual water-supply needs, but it cannot be developed as a replacement strategy for a mine site in general. This is essentially the case encountered at the Highvale Mine site, south of Lake Wabamun (Figures 1 and 2), where the only potential aquifers below the zone of mining are laterally discontinuous sand bodies of fluvial origin within the Horseshoe Canyon Formation (Trudell 1984).

3.1.4 Valley Fill and Outwash Aquifers

This type of aquifer is among the most productive in the plains of Alberta. It consists of sand and gravel deposits within glacial meltwater channels. Upland gravel deposits of Tertiary age are included in this category although they are not related to glaciation. This type of aquifer can occur in two types of settings, either adjacent to the area to be mined or within the boundaries of the proposed mine area. The development strategy is different for the two cases.

In the case of an aquifer adjacent to the area to be mined, the most satisfactory replacement water supply option may be development of a well field and distribution system. If the aquifer is sufficiently productive and the water of sufficiently high quality, economics may justify construction of one or more large diameter production wells. Distribution to individual consumers could be either by trucking or by pipeline, again depending on the economics of the alternatives.

In the event that the gravel or sand aquifer lies within the area to be mined, two alternatives present themselves -- either sterilize a portion of the coal deposit overlain by the aquifer to preserve it for post-mining use, or selectively mine the aquifer material and reconstruct an aquifer following mining. Aquifer reconstruction is discussed in the next section.

It must be stressed that any of these options to develop a sand or gravel aquifer involve considerably increased costs of mining and reclamation. Other water supply options must be absent or poor and the post-mining land use clearly must require a high quantity and quality water supply to justify the economics of developing one of these alternatives.

3.1.5 Spoil Aquifers

The possibility of constructing aquifers within mine spoil, to replace the coal aquifer, has been a topic of considerable interest in western North America for several years, especially in the United States. Our studies indicate that, except in one type of setting, it is highly unlikely that an aquifer could be successfully constructed in mine spoil in the plains of Alberta. The rare case where volumes of sand or gravel adequate to reconstruct an aquifer are present within the overburden is discussed below. In the general case, however, limitation of both inadequate hydraulic conductivity and water quality render such an approach unfeasible.

It has been demonstrated that the Cretaceous rocks of the plains that are associated with coal deposits slake readily when resaturated (Dusseault et al. 1983; Dusseault et al. 1984). As a result, the blocky structure of even the hardest rocks in the overburden, which might be relied upon to create an aquifer framework, breaks down to fine-grained fragments of silt and clay upon exposure to water. Under the load conditions at the base of a spoil mass, this material undergoes compaction, resulting in a further decrease hydraulic conductivity (Scott et al. 1984). Both field and laboratory measurements of hydraulic conductivity of mine spoil in the plains are generally very low (Trudell et al. 1984a).

The chemical quality of water in mine spoil is, in most cases, unacceptable for human and livestock consumption (Trudell et al. 1984a) mainly because of excessive concentration of total dissolved solids and sulfate. Such water could only be used for human consumption by means of extraordinary treatment processes, such as reverse-osmosis systems. In the Whitewood Mine, water that does not exceed concentration limits of any critical constituents has been reported from the spoil (Alberta Environment 1980; Trudell et al. 1984a). This water, however, is not suitable for human consumption for aesthetic reasons, primarily colour and odour.

In the rare case where a sufficient volume of sand and gravel is available in the overburden to reconstruct an aquifer, such a process might be economically feasible. In the past, attention has focused on construction of a widespread confined aquifer at the base of the spoil in the position of the coal. On the basis of our studies, it appears very likely that an aquifer in such a position would contain water of degraded chemical quality as a result of recharge through the overlying spoil. A far more viable alternative would appear to be construction of a more geographically restricted but thicker unconfined aquifer in only a part of the mine area. By placing a sand and gravel fill in an area that will be topographically low in the post-mining landscape, a maximum saturated thickness can be obtained. By designing an open surface drainage network to maximize the amount of area that contributes runoff to the area underlain by the aquifer, both the chemical quality and the amount of water recharging the aquifer would be maintained. Further steps that would assure long-term chemical quality of the water in this aquifer would be inclusion of ponds within the area underlain by the aquifers and construction of subsurface drainage from the aquifer. This latter step would assure that water would flow through the aquifer, thereby preventing the accumulation of salt over time.

It should be stressed again that construction of such an aquifer in mine spoil is possible only in rare cases where sufficient sand and gravel are present in the overburden. The design and construction of such an aquifer represents a significant cost increase, and could be justified only in the face of no viable alternative to provide a water supply of adequate volume and quality to meet post-mining land-use requirements.

3.2 EVALUATION OF EXISTING DATA

This phase of the investigation has two distinct but strongly interrelated components, geology and groundwater. The geologic component is primarily directed at the identification of existing and potential post-mining aquifers and correlation of the stratigraphy of these aquifers over the study area. These aquifers are most commonly bedrock sandstone or coal zones, although at some sites surficial sand or gravel aquifers may be important. The most valuable tools in undertaking this sort of investigation are geophysical logs from test holes. Such logs are usually held by the mining company or utility company involved in the study area, although additional logs in the public domain are available from the offices of the Energy Resources Conservation Board in Calgary, Alberta. Evaluation of existing geologic data should identify potential post-mining aquifers, provide a basis for describing lateral continuity of stratigraphic units and also indicate in which areas additional data are required.

The framework of geologic information outlined above becomes particularly useful in evaluating the available groundwater data. The existing or premining water supply can be characterized by examining domestic water wells and analysing well completion data from water well records held by the Groundwater Information Service, Hydrogeology Branch, Alberta Environment. These data, however, are commonly incomplete and are almost never correlated with local stratigraphy. It is necessary, therefore, to estimate which aquifer (or aquifers) is tapped by individual wells, based on well depth, screened, slotted or open interval (when available) and, in rare cases, water quality. In some cases driller's logs included in the well file may be helpful in determining which aquifer is being utilized. In general, water quality data available from water well records must be approached cautiously. Analyses are commonly incomplete and sample collection, preparation and preservation techniques are unknown. As a rule, these analyses should be considered as an estimate of water quality only; a field sampling program should be considered to adequately characterize premining water quality from domestic wells.

From this compilation of existing geologic and groundwater data, a basic framework for the site is developed. Gaps in the data can be identified and a strategy for the test drilling and instrumentation phase can evolve.

3.3 TEST DRILLING AND INSTRUMENTATION

This phase of the investigation has two primary objectives. The first is to complete the data base required for geologic/ stratigraphic characterization of the principal aquifers in the area, particularly those that occur below the zone of mining, as well as to explore for new aquifers. The second is to provide a means of testing each aquifer at a number of locations, in order to determine its hydraulic properties and water quality characteristics, and the distribution of these parameters over the study area.

In the Battle River study area (Figure 1), for example, the Plains Hydrology and Reclamation Project utilized 14 sites within a study area of approximately 160 km^2 (Trudell et al. 1984b). In that study area, the geology is relatively laterally continuous, and 14 sites were found to be adequate to characterize both the stratigraphy of sheet-like sandstone aquifers below the zone of mining, as well as the lateral distribution of hydraulic properties and water quality.

The selection of sites for the investigation of post-mining water supply potential should take into consideration the potential for local geologic features to impact the groundwater in aquifers at depth, as identified in the exploration strategy. In particular, features such as valley fill sediments or buried channel deposits, in addition to being potential aquifers in their own right, may act to introduce fresh water recharge to deeper aquifers, thereby causing significant changes in the deep water quality. In the Battle River study area, for example, work from the Plains Hydrology and Reclamation Project revealed that groundwater from a thick sequence of sediment of Quaternary age in the valley of Paintearth Creek was recharging a sheet-like sandstone aquifer within the Bearpaw Formation (approximately 80 m below surface) (Trudell et al. 1984b). The resulting chemical makeup of water in this deep sandstone aquifer down-gradient from the zone of recharge was typically 1100 to 2500 mg/L total dissolved solids, sodium-bicarbonate type water. In areas not influenced by the local recharge, the water in this aquifer was of sodium-chloride type with total dissolved solids of approximately 3000 to 3500 mg/L.

A typical test site consists of several individual piezometers, collectively referred to as a nest, completed in various potential aquifers at different depths. The deepest drill hole at each site is logged using geophysical techniques; in the Plains Hydrology and Reclamation Project it was found that a gamma ray-density-caliper log was the most useful for purposes of stratigraphic correlation. The geophysical logs, together with the descriptive log of cuttings from the testhole, are used to identify zones for instrumentation.

In order to facilitate monitoring and sampling the instrumentation used by the Plains Hydrology and Reclamation Project consisted primarily of 5.0 cm diameter PVC piezometers, although sizes ranging from 1.9 to 5.0 cm diameter are commonly used in such investigations. These piezometers are screened over a relatively small interval (relative to the thickness of the stratigraphic column under study), generally ranging from 1 to 3 m. The screened interval should be less than or equal to the thickness of the hydrostratigraphic unit to be investigated. Completion of piezometers involved the placement of a silica sand pack around the screen, with a bentonite seal above the sand pack (for piezometers less than 40 m deep) and cement grout to ground surface.

3.4 HYDRAULIC TESTING AND WATER SAMPLING

The hydraulic properties of potential aquifers can be determined by single-well response tests or pumping tests. Such testing is used to provide a measurement of hydraulic conductivity (or transmissivity), and in some cases storativity of the aquifer. In areas where the geologic and hydrologic conditions are reasonably well known, single-well response tests (slug tests) (Cooper et al. 1967; Hvorslev 1951; Freeze and Cherry 1979) are a valuable means of determining the lateral distribution of aquifer hydraulic properties for a study area. Since these tests are of a very short duration (several minutes to a few hours), however, it is advisable to consider supplementing single-well response tests with at least one pumping test in each aquifer that displays potential as a post-mining water supply. Also, pumping tests can provide a value of well yield based on actual measurements, whereas single-well response tests provide only values of transmissivity. In this case, an approximate well yield can be calculated from the transmissivity, with available drawdown determined from water level measurements, by using a version of the equations developed by Cooper and Jacob (1946).

In addition to hydraulic properties, the water quality characteristics of available aquifers must be determined. At this stage, domestic water wells should be sampled in order to describe the premining water quality enjoyed by local residents. This will become the yardstick by which any alternative supply is judged, and is therefore the water quality target for each potential post-mining aquifer. Although domestic water wells provide a useful indication of overall premining water quality, they are generally not suitable for use in characterizing the water quality in individual aquifers. This is because of uncertainties in well completion information, typically long screened or open intervals allowing mixing of water from different aquifers, and water quality artifacts associated with various well construction techniques.

The characterization of water quality in potential post-mining aquifers should be based on water samples from piezometers or test wells, for reasons discussed in the preceding paragraph. Such samples insure that water is taken from a single aquifer only. All piezometers and test wells should be thoroughly developed before sampling to remove all traces of drilling water from the well or piezometer. In addition, at least one and wherever possible four to six well-bore volumes of standing water should be removed from the well immediately prior to sampling, to insure that a fresh sample is collected (Schuller et al. 1981). Samples for the characterization of water quality in an aquifer are typically analysed for major ionic constituents (Ca^{2+}, Mg^{2+}, Na^{+}, K^{+}, $SO_4^{=}$, Cl^{-}, $CO_3^{=}$ + HCO_3^{-}, NO_3^{-}), total dissolved solids, pH, plus field analyses of unstable species such as iron and sulfide. Samples may also be collected and analysed for trace constituents (such as antimony, arsenic, boron, cadmium, cobalt, copper, lead, mercury, and selenium) where warranted. During development and sampling the presence of gas and such aesthetic factors as colour, odour, and, where appropriate, taste should be noted.

3.5 SYNTHESIS AND INTERPRETATION

The data compiled in the first three phases of the investigation form the basis for evaluating the post-mining water supply potential of a site. In order to assess the suitability of an aquifer to serve as a post-mining water supply, it is necessary to compare its characteristics to those of the existing water supply. This involves quantifying the characteristics of both the existing supply and the potential replacement. It is worthwhile to bear in mind that the objective here is to find a suitable replacement groundwater supply, not to attempt to duplicate the existing supply. To this end, it must be recognized that a certain degree of variance between existing and replacement supply is inevitable, within certain limits. This applies to both well yield and water quality characteristics.

One aspect of the characterization of the premining groundwater supply conditions is the intensity of groundwater exploitation in a mining area. This can be expressed in terms of the number of domestic wells per unit of land area, and provides an indication of the extent to which the groundwater resource is utilized prior to mining, as well as the likely density of wells in the reclaimed landscape. Because most of the surface coal mines in

Alberta are situated in agricultural areas with low population density, it is suggested that an area of 10 km^2 is a useful unit to serve as a basis for evaluating intensity of groundwater exploitation. For example, in the Battle River mining area the intensity of groundwater exploitation is 3.6 domestic wells per 10 km^2; in the Highvale mining area the intensity is 9.2 wells per 10 km^2. The intensity in the Battle River mining area is probably typical of agricultural areas in central Alberta; the Highvale mining area also includes wells located in the relatively densely-populated area of recreational properties along the shore of Lake Wabamun and, therefore, is probably not representative of exclusively agricultural areas. In cases such as the Highvale mining area, where the density of domestic wells varies greatly, it may be useful to also determine the range of groundwater exploitation intensity based on a smaller unit of area than described above. For this purpose, the number of wells per section of land (that is, 2.6 km^2, or 1 mi^2, as used by the Dominion Land Survey) is probably a realistic area-based intensity. Since well records in the Alberta Environment data files are organized according to legal land location (including section numbers), this provides a rational basis for grouping wells by section. The values of groundwater exploitation intensity determined on a section basis may range from zero to several tens of wells per section. The small areas of high-intensity exploitation may demand different treatment in terms of mining, reclamation, and post-mining land use considerations.

The characterization of both existing and replacement groundwater supplies has two components -- water quantity (yield) and water quality. Although both of these components can be expressed in either relative (based on comparison of replacement to existing) or absolute (compared to a set value) terms, water quantity requirements can be more easily defined in absolute terms than can water quality limits. A minimum acceptable well yield can be determined based on available domestic water use data. In a report titled "Soil Testing and Groundwater Supply Evaluation Guidelines for Residential Subdivisions" (Alberta Environment 1983, pp. 8-9) the following statement is made regarding the water supply requirements for a single household:

> "The requirements are currently calculated, assuming water consumption is an average of 1091 litres/day/lot (240 Imperial gallons/day/lot). These requirements include an amount necessary for human consumption and sanitary purposes, but do not provide for fire protection, irrigation, livestock, or any other outdoor requirements."

Because of the restriction on nonhuman uses, this figure is considered to represent a minimum value. According to Hammer (1977), the average daily water use in the western United States is 1700 L/d per residence. Both of these figures are daily averages. In calculating water supply requirements (without storage) it is common engineering practice to use the maximum hourly demand as the design criterion; a mean maximum hourly rate is typically 3.6 times the daily average (Hammer 1977). Consequently, the maximum hourly rate for the design of a water supply would range from 164 L/hr (Alberta) to 255 L/hr (western United States). These rates correspond to 0.05 L/s to 0.07 L/s.

The well-yield values determined from short-term pump tests or single-well response tests are based on a number of assumptions and simplifications, and also represent the testing of a relatively small volume of aquifer material. To accommodate these effects a factor of safety of at least 50 percent is commonly included in the calculation of well yields. In recognition of this, the required well yield (determined from short-term tests) to adequately supply the domestic requirements specified above (0.05 to 0.07 L/s) should be at least 0.08 to 0.10 L/s. Individual users whose peak needs exceed the average may accommodate such requirements by the use of water storage facilities at the surface.

The interpretation of water quality characteristics is much more subjective. There are essentially two cases to deal with; (1) constituents for which maximum permissible concentrations are clearly defined, that is, those chemical species that have a known serious adverse effect on human health and consequently have a maximum permissible concentration defined by safety to humans. Such species include certain trace metals, organic chemicals, and radionuclides (McNeely et al. 1979). In this case the existing water supply and the replacement water supply are compared to the specified standard. Case 2 applies to constituents for which maximum permissible concentrations (based on health concerns) are not well defined, that is constituents for which concentration limits are arbitrarily set, primarily for aesthetic reasons. Total dissolved solids and sulfates are examples. Although high concentrations of these constituents may cause some discomfort when first consumed, once accustomed to consuming such water it is not uncommon for people to drink this water for their entire lives without serious adverse health effects. In this case, the characteristics of the existing water supply is used to define a local objective concentration, on relative standard concentration; which then becomes the basis for comparing the existing and replacement water supplies. In other words, the objective of a post-mining groundwater supply is to meet or exceed the water quality of existing domestic wells, which has proven to be acceptable to local residents. Within a study area, however, there will inevitably be a range of water qualities from a given number of domestic wells; therefore, it is necessary to describe this range of values. This range of water quality can be conveniently illustrated by means of a cumulative frequency curve for data from the population of domestic wells as well as for the potential replacement water supply, as illustrated in Figure 3.

The following example illustrates the use of the cumulative frequency distributions for these two cases. Figure 3 is a plot of the cumulative frequency distributions of concentration (of any given ionic species) for two hypothetical groups of water samples, A and B. For the purpose of illustration, the group A samples might be from domestic water wells, and group B from a potential replacement water supply. In this example, the class size is 20 mg/L, so that the first class is from 0 to 20 mg/L, the second is from 21 to 40 mg/L,

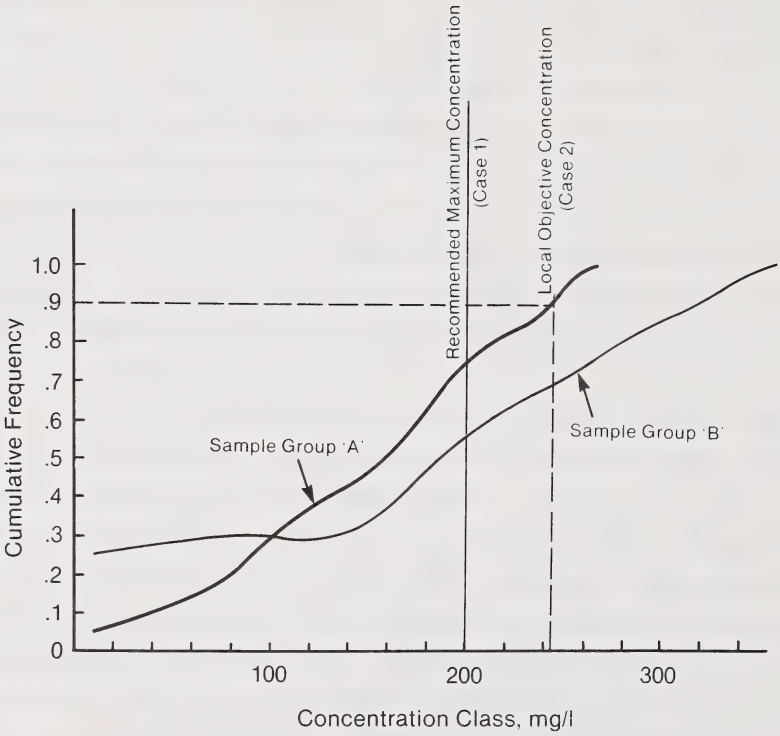

Figure 3. Example cumulative frequency distributions for two groups of water samples, A and B.

and so on. In the first case, upon examining the curves at the hypothetical maximum allowable concentration of 200 mg/L, for instance, it can be seen that 73 percent of the samples from group A have a concentration less than 200 mg/L; similarly, 55 percent of the samples from group B have a concentration of less than 200 mg/L. Clearly, from a water quality standpoint, this suggests that group A is more desirable than B. At concentrations above 200 mg/L the difference between the two groups becomes even more pronounced. One hundred percent of the samples from A have concentrations less than 280 mg/L, whereas only 77 percent of the samples from B have less than 280 mg/L. At concentrations below 200 mg/L the difference between the two groups is less pronounced; 30 percent of samples from both A and B have concentrations less than 100 mg/L (the point at which the two curves cross). Below 100 mg/L, group B tends to be somewhat better than A. Overall, however, considering particularly the percentage of samples having less than the maximum allowable concentration, group A clearly has the better water quality of the two.

In the second case, a local objective concentration might be defined, for example, as the concentration corresponding to the 90th percentile of the cumulative frequency distribution (or C_{90}) of the reference sample group. In the example illustrated in Figure 3, the local objective concentration might be defined as the value corresponding to the 90th percentile of group A (domestic water well samples), or 244 mg/L. In this case, 90 percent of the group A samples are less than 244 mg/L (by definition), compared to only 68 percent of the group B samples. In this example, the conclusion would probably be reached that B is not a desirable substitute for A.

This approach acknowledges the fact that in any large group of water samples there is likely to be a small percentage of samples with exceptionally high (or low) concentrations, and that it is probably not reasonable to use either maximum or minimum values as reference concentrations. Similarly, mean concentrations are less than ideal for two reasons: (1) They correctly apply only to normally distributed populations (which are not always encountered); and (2) The critical concentration, in terms of domestic consumption, is toward the upper end of the range of values. For example, the mean concentration from an aquifer may be below the recommended limit, but 40 percent of the samples may exceed the limit; clearly it would not be a desirable water supply. This process of evaluation will provide an indication of how well a post-mining water supply measures up to the premining supply. No attempt, however, is made in this report to define the magnitude of deviation between existing and replacement water supplies that is considered to be acceptable.

The final analysis of replacement water supply potential for a site is a compilation of settings (both in the vertical dimension, by aquifer, and in the horizontal dimension, within an aquifer), in which the specified criteria of water quality and quantity are met. In addition, individual aquifers that meet these criteria can also be ranked according to their potential for contamination by groundwater of degraded quality. The results of this compilation can be conveniently illustrated by the use of a map or maps, indicating the lateral distribution of zones of suitable post-mining water supply over the study area.

4. CONCLUSIONS

The evaluation of post-mining water supply potential for a study area involves a review of available geologic and hydrogeologic data, a field investigation designed to characterize existing and potential post-mining water supply, and a compilation of zones of suitable groundwater quality and quantity. It is conceivable that after this evaluation, areas will be found in which no viable post-mining water supply exists. In some such areas, use of exceptional water treatment procedures (for areas with inadequate water quality as the limitation) may be applied, or an alternative to on-site groundwater may be required. Such alternatives include pipelining, trucked-in water, or surface water. In any event, it is necessary to recognize that some loss of the groundwater resource inevitably accompanies the surface mining of coal, and this loss is part of the cost associated with the exploitation of the coal resource.

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